Guidance on the Preparation of Exceptional Events Demonstrations for Wildfire Events that May Influence Ozone Concentrations

(Section 3 only)

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Acronyms

AGL	Above ground level
AQS	Air Quality System
CAA	Clean Air Act
CAMx	Comprehensive Air Quality Model with Extensions
CARB	California Air Resources Board
CFR	Code of Federal Regulations
CMAQ	Community multiscale air quality model
CO	Carbon monoxide
DDM	Direct decoupled method
EER	Exceptional Events Rule
EPA	Environmental Protection Agency
FINN	Fire inventory from the National Center for Atmospheric Research
FIPS	Federal Information Processing Standards
GDAS	Global data analysis system
HYSPLIT	Hybrid single particle lagrangian integrated trajectory model
K	Potassium
km	Kilometers
mb	Millibars
MDA8	Maximum daily 8-hour average for ozone
MODIS	Moderate Resolution Imaging Spectroradiometer
NAAQS	National Ambient Air Quality Standard or Standards
NAM	North American mesoscale forecast system
NCAR	National Center for Atmospheric Research
NDAS	North American mesoscale data analysis system
NEI	National Emission Inventory
NO	Nitrogen oxide
NOx	Nitrogen oxides
NO_2	Nitrogen dioxide
NWS	National Weather Service
O_3	Ozone
PM	Particulate matter
PM_{10}	Particulate matter with a nominal mean aerodynamic diameter less than or equal to 10 micrometers
$PM_{2.5}$	Particulate matter with a nominal mean aerodynamic diameter less than or equal to 2.5 micrometers
ppb	Parts per billion

Q/D	24-hour fire emissions, in tons per day, divided by the distance of the fire to the monitor, in kilometers
ROG	Reactive organic gases
rVOC	Reactive volatile organic compounds
SIP	State implementation plan
SMARTFIRE	Satellite Mapping Automated Reanalysis Tool for Fire Incident Reconciliation
TOG	Total organic gases including methane and other reactive volatile organic compounds
VOC	Volatile organic compounds
WRF-CHEM	Weather research and forecasting model coupled with chemistry

3. Clear Causal Relationship Between the Specific Event and the Monitored Concentration

3.1 Overview and EER Provisions

The 2016 EER revisions require that demonstrations address the technical element that "the event affected air quality in such a way that there exists a clear causal relationship between the specific event and the monitored exceedance or violation (supported in part by the comparison to historical concentrations and other analyses)." This section of the demonstration provides evidence supporting the clear causal relationship between the event and the monitored NAAQS exceedance or violation and, therefore, that the event has affected air quality. Air agencies should support the clear causal relationship with a comparison of the O_3 data requested for exclusion with historical concentrations at the air quality monitor. In addition to providing this information on the historical context for the event-influenced data, a clear causal relationship is generally established by demonstrating that the fire's emissions were transported to the monitor, the fire's emissions affected the monitor, and in some cases, a quantification of the level of impact of the fire's emissions on the monitored O_3 concentration.

3.2 Event-related Concentration in the Context of Historical Concentrations

Part of demonstrating a clear causal relationship between the event and the monitored O_3 exceedance involves a comparison with historical concentrations measured at the monitor or throughout the area during the same season. Air agencies should compare the data requested for exclusion with the historical concentrations at the monitor, including all other "high" values in the relevant historical record. If other values in the historical record are alleged to have been affected by exceptional events, the EPA recommends identifying those values and including event information to support that the monitored concentrations were impacted, such as a list of previous fire dates and locations. In addition to demonstrating how the level of the event exceedance compares with historical data, it may also be useful to demonstrate how the diurnal or seasonal pattern differs, if such a deviation occurred, due to the event. To be effective, such comparisons need some level of robustness. Statistical summaries used to characterize non-event, high-concentration day historical data and the differences seen on event days would carry more weight than anecdotal or general assertions of when non-event behavior occurs, without evidence or quantification.

The data used in the comparison of historical concentrations analysis should focus on concentrations of O_3 at the impacted monitor and nearby monitors if appropriate. Evidence of additional impacts on air quality [carbon monoxide (CO), particulate matter (PM), nitrogen oxides (NOx), etc.] can also be provided if they provide additional insight.

There is no pass or fail threshold for the historical concentrations data presentation. However, the comparisons may inform the additional evidence needed to successfully establish the clear causal relationship element. For example, historical comparisons conclusively showing that the event-affected O_3 concentration was outside the range of historical concentrations will likely indicate less additional evidence may be needed to demonstrate the clear causal relationship. The

seasonality of the event-related exceedance versus other exceedances may be used to determine if a Tier 1 (Section 3.4) demonstration may be an appropriate option. Additionally, the percentile ranking of the event-influenced data against historical data may also be used in one of the factors (Section 3.5) to determine if a Tier 2 demonstration may be a suitable option.

3.2.1 Examples of Supporting Documentation

- Provide a plot of the maximum daily 8-hour O_3 concentrations at the monitor(s) in question for the high O_3 seasons (April through October, or other months as appropriate) for at least 5 years. An example approach to plotting these data is shown below in Figure 2. Alternatively, including separate plots for each year (or season) may also be an informative approach to presenting this information.
- Timeseries plots of O_3 concentrations at nearby monitors to demonstrate spatial variability of O_3 in the area.
- Determine 5-year percentile of the data requested for exclusion on a per monitor basis.
- Determine the annual ranking of the data requested for exclusion. This assessment may be potentially helpful to show when the non-event O_3 during the year with the exclusion request was lower than surrounding years.
- Identify the cause of other "peaks" – fires, other causes, or normal photochemical events, and provide evidence to support the identification when possible.
- A timeseries plot covering 12 months (or the months of the high O_3 season) overlaying all 5 years of data plotted can be useful in identifying monitored concentrations that are unusually high for a time of year, and/or that coincide with fire events. An example is provided below in Figure 3.
- Trends due to emission reductions from planning efforts, or other variability due to meteorology or economics of an area can be discussed in explaining the distribution of data over the previous 5 years.

Figure 2. Example of an O_3 time series plot from an event-impacted monitor to include in a demonstration.

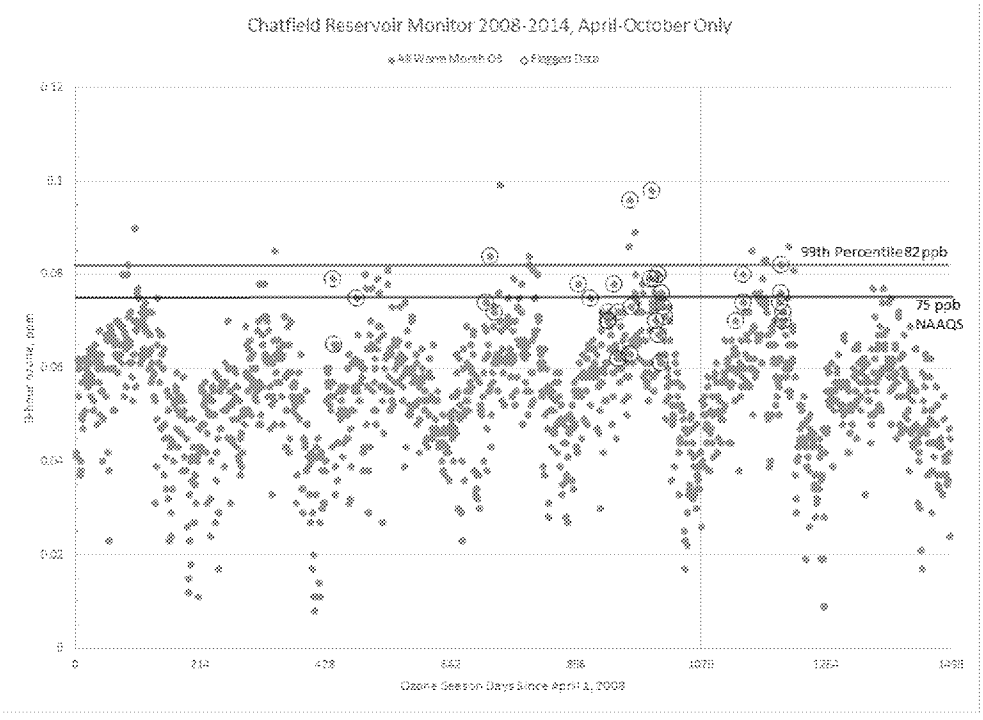
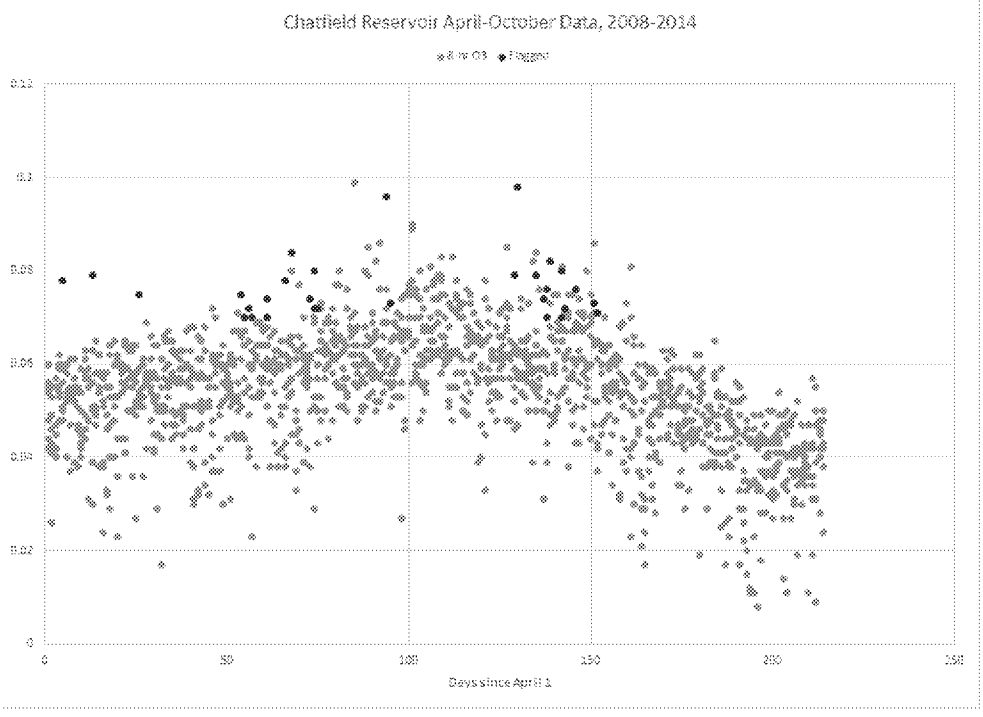


Figure 3. Example of a seasonal O_3 plot, overlaying multiple years of data from an event-impacted monitor to include in a demonstration.



3.3 Concept of Different Tiers of Exceptional Events Demonstrations

The nature and severity of a fire event will, in part, determine the evidence that an air agency will need in its weight of evidence showing for the clear causal relationship portion of an exceptional events demonstration for fire impacts on monitored O_3 concentrations. The tiering strategy described in this guidance contains three tiers of demonstrations and is based on an event's potential for O_3 formation at a given monitor and/or the history of non-event O_3 concentrations at the monitor. This strategy acknowledges that some fire events can be extreme or otherwise clearly stand out from normally occurring O_3 concentrations and, thus, may necessitate less evidence for the clear causal relationship analysis.

Tier 1 demonstrations are appropriate for the clearest events, *e.g.*, fires located in close proximity to a monitor in an area or during a time of year with typically low O_3 concentrations. Tier 1 demonstrations would likely need the least amount of evidence. Tier 2 demonstrations would be used in situations with less clear fire impacts and would thus require more evidence than Tier 1 demonstrations. Tier 3 demonstrations, requiring more evidence than Tier 2 demonstrations, would be appropriate when the relationship between the subject fires and influenced O_3 concentrations is complex. Section 3.4 defines situations where a Tier 1 demonstration may be appropriate, Section 3.5 defines situations and evidence suggested for a Tier 2 demonstration, and Section 3.6 suggests additional evidence that may be necessary for a Tier 3 demonstration.

3.4 Key Factor of and Suggested Evidence to Include in Tier 1 Demonstrations

The EPA expects that Tier 1 exceptional events demonstrations may be appropriate for fire events that have a clear impact on O_3 concentrations when they occur in an area that typically experiences lower O_3 concentrations, are associated with an O_3 concentration that is clearly higher than non-event related concentrations, or occur outside of the area's normal O_3 season. In these situations, O_3 impacts should be accompanied by clear evidence that the fire's emissions were transported to the location of monitor. This tier of demonstration is expected to be the most simple and easiest to prepare.

3.4.1 Evidence the Event, Monitor(s), and Exceedance Meet the Key Factor for Tier 1 Demonstrations

Key Factor – Seasonality and/or distinctive level of the monitored O_3 concentration: The key factor that delineates event-related monitored O_3 concentrations for Tier 1 demonstrations is the uniqueness of the concentration when compared to the typical seasonality and/or levels of O_3 exceedances. For example, if an event-related exceedance occurs during a time of year that typically has no exceedances, then that event-related exceedance may be more straightforward to attribute as having been due to the fire than event-related concentrations that occur during the same month or season as typical high O_3 concentrations. If there are other exceedances during the same time of the year as the fire-related exceedance, for example during normal O_3 season, they either should also be attributable to fire (or other exceptional events) or if attributable to normal emissions and photochemistry they should be clearly lower in magnitude than the fire-related concentrations. The EPA recommends that event-related exceedances should be at least 5-10 ppb higher than non-event related concentrations for them to be clearly distinguishable. This key factor is based on the fact that if there are no similar-level non-event exceedances

mixed in with the event-related exceedance, then less evidence may be necessary to demonstrate the clear causal relationship between the event and the monitored O_3 concentration. Following are two types of analyses that an air agency can provide for this section of the demonstration.

1) Provide a timeseries plot covering 12 months (or the typical O_3 season months plus months with the event-related exceedance) overlaying at least 5 years of O_3 monitoring data. An example is shown in Figure 3.
2) Provide a description of how the seasonality of the event-related exceedance differs from the typical photochemical O_3 season and how other exceedances, if any, during the time of year of the fire-related exceedance are not attributable to normal emissions and photochemistry, are attributable to fire (or other exceptional events), or are clearly lower in magnitude than the fire-related concentrations.

3.4.2 Evidence the Fire's Emissions Were Transported to the Monitor(s)

In addition to the evidence suggested in Section 3.4.1, the air agency should supply at least one piece of additional evidence to support the weight of evidence in a Tier 1 demonstration that the emissions from the fire were transported to the monitor location (*i.e.*, the latitude and longitude). Air agencies can use either a trajectory analysis or a combination of satellite and surface measurements to show this transport. This evidence could be any of the following:

- *Trajectory analysis.* Atmospheric trajectory models use meteorological data and mathematical equations to simulate three-dimensional transport in the atmosphere. Generally, these models calculate the position of particles or parcels of air with time based on meteorological data such as wind speed and direction, temperature, humidity, and pressure. Model results depend on the spatial and temporal resolution of the atmospheric data used and also on the complexity of the model itself. The HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) model is frequently used to produce trajectories for assessments associated with air quality programs. HYSPLIT contains models for trajectory, dispersion and deposition. However, analyses applicable to exceptional events demonstrations typically use the trajectory component. The trajectory model, which uses existing meteorological forecast fields from regional or global models to compute advection (*i.e.*, the rate of change of an atmospheric property caused by the horizontal movement of air) and stability, is designed to support a wide range of simulations related to the atmospheric transport of pollutants.

  Air agencies can produce HYSPLIT trajectories for various combinations of time, locations and plume rise. HYSPLIT back-trajectories generated for specific monitor locations for days of high O_3 concentrations illustrate the *potential* source region for the air parcel that affected the monitor on the day of the high concentration and provide a useful tool for identifying meteorological patterns associated with monitored exceedances. Forward-trajectories from specific fire events to specific monitors can also be used to indicate *potential* receptors. HYSPLIT trajectories alone cannot definitively conclude that a particular region contributed to high pollutant concentrations, but a set of HYSPLIT trajectories that show no wind flow from a particular region on days with high concentrations might support discounting that region as contributing to the concentrations.

Air agencies could use other trajectory models, such as FLEXPART to demonstrate expected transport. Appendix A3 contains additional information on trajectory analyses.

- *Satellite Imagery of Plume with Evidence of the Plume Impacting the Ground.* Because plume elevation is not directly available from simple imagery, plume imagery alone does not conclusively show that fire emissions transported aloft reached a ground-level monitor. If plume arrival at a given location coincides with elevation of fire plume components (such as $PM_{2.5}$, CO or organic and elemental carbon) those two pieces of evidence combined can show that smoke was transported to the event location.

3.5 Key Factors of and Suggested Evidence to Include in Tier 2 Demonstrations

The EPA expects that additional evidence may be required for Tier 2 demonstrations, in comparison to Tier 1 demonstrations. To delineate key factors where Tier 2 demonstrations may be appropriate, the EPA reviewed approved exceptional events demonstrations, conducted a literature review of case specific fire-O_3 impacts, and completed photochemical modeling analyses.

Literature review: Fires can impact O_3 concentrations by emitting O_3 precursors including NOx and VOCs. These precursor emissions can generate O_3 within the fire plume or can mix with emissions from other sources to generate O_3 (Jaffe and Wigder, 2012). Also, in some situations, including near fires, reduced O_3 concentrations have been observed and attributed to O_3 titration by enhanced NO concentrations and reduced solar radiation available to drive photochemical reactions (Jaffe et al., 2008; Yokelson et al, 2003). The magnitude and ratios of emissions from fires vary greatly depending on fire size, fuel characteristics, and meteorological conditions (Akagi et al., 2012). As a result of variable emissions and non-linear O_3 production chemistry, the O_3 production from fires is very complex, highly variable, and often difficult to predict (Jaffe and Wigder, 2012).

Despite the complexities in predicting O_3 formation from fire emissions, several studies have found increases in O_3 concentrations attributable to fire impacts. For example, Pfister et al. analyzed surface O_3 data during a high wildfire year in California (2007) with modeled fire impacts and found monitored 8-hour O_3 concentrations were approximately 10 ppb higher when the modeled fire impacts were high (Pfister et al., 2008). Jaffe et al. analyzed three wildfire periods in the western U.S. during 2008 and 2012 and compared monitored surface O_3 concentrations with two different modeled estimates of fire contributions to O_3 concentrations to find enhancements in O_3 when fire impacts were predicted to be high (Jaffe et al., 2013). Many other publications have found similar relationships between surface O_3 and fire occurrences, using a variety of technical approaches (Bytnerowicz et al., 2013). One literature study was used to evaluate the relationship between O_3 impact and fire characteristics (Jaffe et al., 2013).

Empirical Relationships between Fire Events and O_3 Concentrations in Previous Demonstrations: The EPA reviewed previous demonstrations for specific fire events to determine if general relationships exist between the magnitude of the fire emissions and the distance of the fire to O_3 monitors. Between 2010 and September 2015, the EPA approved two exceptional events demonstrations for fire-related impacts on O_3. The first was approved in

2011. In this case, the EPA concurred on three exceedances of the 1-hour O_3 NAAQS near Sacramento, California in 2008 due to a series of lightning-initiated wildfires throughout northern California. The second demonstration for fire impact on O_3 was approved in 2012. In this case, the EPA concurred with the exclusion of eight 8-hour daily maximum O_3 exceedances during April 2011 in Kansas due to impacts from prescribed fires and wildfires. Prescribed fires caused most of the exceedances identified in the Kansas demonstration.

Modeling Studies of O_3 Impacts from Fires: To support the development of this guidance and to assess the relationship between fire source strengths and resultant O_3 concentrations at various distances from the fire (Appendix A2), the EPA conducted modeling analyses for fires identified in the EPA's 2011 National Emissions Inventory (NEI). Four fires of varying strengths and locations were simulated with the Community Multiscale Air Quality Model (CMAQ) model. The O_3 impacts of these fires were estimated using a source apportionment technique (Kwok et al., 2015). Consistent with previous literature studies, the EPA modeling suggests that NOx and VOC emissions can lead to significant increases in O_3 concentrations downwind of the fire. The simulated O_3 increases are related to distance downwind from the fire emissions and the magnitude of the fire emissions. This modeling suggests that it is appropriate to use a simple Q/D (emissions/distance) metric to conduct a screening assessment of potential fire impacts. This model application was evaluated against monitoring data and appears to capture the ambient relationships between CO and O_3 measured in the vicinity of smoke plumes. The EPA acknowledges that the science continues to emerge in modeling the O_3 impacts of fires (*e.g.*, plume chemistry, plume rise). The 2011 modeling includes some limited treatment of the sunlight-blocking impacts of smoke on O_3 photochemistry.

The EPA used the general relationships between O_3 impacts and fire characteristics from the modeling study, in combination with the assessment of previously approved demonstrations and fire case-studies from the peer-reviewed literature to develop two key factors (Section 3.5.1) for a Tier 2 demonstration. Section 3.5.1 includes a recommended value and guidance for determining Q/D.

3.5.1 Evidence that the Event, Monitor(s), and Exceedance Meet the Key Factors for Tier 2 Demonstrations

This section details the evidence to be included in a Tier 2 demonstration for the clear causal relationship rule element.

Key Factor #1 – Fire emissions and distance of fire(s) to affected monitoring site location(s): At least one air quality related program (*i.e.*, determining impacts at Class I areas) uses an emissions divided by distance (Q/D) relationship as a key factor for determining the influence of emissions on a downwind monitor. The EPA believes that it is appropriate to use a similar approach, along with key factor #2 detailed below, to determine if a Tier 2 exceptional events demonstration provides sufficient evidence to satisfy the clear causal relationship criteria of the EER for fire O_3 demonstrations. To determine an appropriate and conservative value for the Q/D threshold (below which a full/Tier 3 exceptional events demonstration would be recommended), the EPA conducted a review of approved exceptional events demonstrations, a literature review of case specific fire-O_3 impacts, and photochemical modeling analyses as described above. The three analyses generally showed that larger O_3 impacts occurred at higher Q/D values. The reviews

and analyses did not conclude that particular O_3 impacts will always occur above a particular value for Q/D. For this reason, a Q/D screening step alone is not sufficient to delineate conditions where sizable O_3 impacts are likely to occur. Given this, the EPA recommends, as the first of two key factors, that the Q/D (as described below) should be $\geq$ 100 tons per day/kilometers (tpd/km). The rationale for the recommendation of $\geq$ 100 tpd/km as a conservative indicator of O_3 impacts is based on the Q/D ratio for previously approved fire-related O_3 exceptional events demonstrations and the modeling results that showed the largest O_3 impacts were often associated with high Q/D values. The O_3 values within the approved demonstrations generally were associated with Q/D values above 50 tpd/km (Figure A2-1), though not all the concentrations shown were clear decisions. The largest O_3 impacts from the modeling studies of the two largest fires (Wallow and Flint Hill fires) were associated with Q/D values above 100 tpd/km (Figure A2-5), and large O_3 impacts were not observed in the modeling of the two smaller fires (Big Hill and Waterhole fires). Based on results from these analyses and reviews, if the Q/D (as defined and calculated in Section 3.5.1) is $\geq$ 100 (tpd/km), then a Tier 2 demonstration may be appropriate (assuming key factor #2 is also met). Following is a description of how an air agency could develop a Q/D analysis.

Calculate Q/D for the event and monitor pairs:

Determine fire emissions (Q): For the purposes of exceptional events tiering, fire emissions (Q in the Q/D expression) is defined as the daily sum of the NOx and reactive-VOC emissions (in units of tons per day) from specific fire events impacting the O_3 monitor on the day of the O_3 exceedance. Air agencies should describe and characterize in the event summary section of the demonstration all fires included in the calculation of Q/D. Since a fire event can span several days and because fire emissions may not impact a monitor on the day that they are generated, this guidance suggests the following approach for assessing a range of days to determine the maximum Q/D value to use for the screening test:

1) Determine the date of the 1st hour in the period of the 8-hour (or 1-hour) O_3 average that is the subject of the demonstration. *Example*: August 15, 2014.

2) Determine the date of the 8th hour of that 8-hour period, which may be the same as the first date or the following date. *Example*: August 16, 2014.

3) Identify fires generating emissions on these one or two dates and identify the date prior to the date of the 1st hour. Including the latter date allows for the possibility that fire emissions on one day affected ozone on the next day. These are the two or three dates that will be included in assessing the clear causal relationship. *Example*: August 14, 15, and 16.

   The EPA recommends generating 24-hour back trajectories from the affected O_3 monitoring site(s) beginning at each hour of these two or three dates. Identify fires that are close to any of these back trajectories. *Example*: the air agency identifies three fires: Fire A, Fire B and Fire C.

4) Identify the latitude/longitude of each fire for each day. Determine "D," the distance in kilometers between the fire's latitude/longitude and the affected O_3 monitor for each fire for each day.

5) For each fire and each day, identify the sum of NOx and reactive VOC (rVOC) emissions in tons/day. If only TOG emissions (versus rVOC) are available, multiply the TOG emissions by 0.6 to represent the reactive fraction that can contribute to O_3 formation (*see* Appendix A2). Alternatively, sum the specific rVOC emissions or use a multiplier other than 0.6 with appropriate justification. This step is designed to account for the fact that some of the gases included in the TOG emissions estimates to not contribute to ozone formation.

   Day-specific emissions estimates should be readily available for wildfire (and prescribed fire events) that occur during NEI years using the EPA methods. In addition to the actual emissions estimates (NOx, VOC, CO, SO_2, PM tons/day), the NEI methods also result in many other data fields that will be made available (date of fire occurrence, fire event name, state/county FIPS, latitude, longitude, quality assurance flag, fire type, acres burned). Detailed information about how the EPA develops inventories for fires on wildlands is part of the latest NEI documentation available on CHIEF (*http://www3.epa.gov/ttn/chief/eiinformation.html*). In general, the EPA's approach for estimating fire emissions relies on a combination of satellite detection of fires merged with on-the-ground observational data (especially with activity data submitted by local air regulatory and forestry agencies) and where available combined with models that specify fuel loading, fuel consumption, and emission patterns/factors. These emissions are based on the latest version of the Satellite Mapping Automated Reanalysis Tool for Fire Incident Reconciliation (SMARTFIRE) system (*http://www.airfire.org/smartfire/*). Air agencies can provide fire event emissions and activity data as part of an exceptional events demonstration that the state believes more accurately characterize the event than the information contained in the NEI, provided those emissions and activity data are well-documented and supported.

   To estimate fire-related emissions in non-NEI years, air agencies may use other techniques to represent fire emissions, especially methods that have been agreed upon by multiple public agencies (*e.g.*, *http://www.airfire.org/data/playground/*) or emission estimates that reside in the published literature. The fire activity data and emissions estimation techniques used should be well-documented and supported. However, the EPA encourages the use of ground-based observations and local fuel information whenever possible as these factors can significantly improve the resulting estimates of fire emissions. As resources allow, to assist air agencies in locating fire-related emissions in non-NEI years, the EPA anticipates

providing year and day-specific fire event emissions summaries using similar methodologies to that used in the NEI.

6) Check the fires individually to see whether any one of them had Q/D >100 for any of the days. If yes, evaluate key factor #2.

7) If no, determine whether the fires satisfy the Q/D test when aggregated. For each day of fire, weight the distances between the fire locations and the O_3 monitor by the NOx+rVOC emissions for that day to get an emissions-weighted D. Sum the NOx+rVOC emissions of all three fires (*e.g.*, Fire A, Fire B and Fire C from the above example) from the day, and calculate Q/D using the emissions sum and the distance.

8) If Q/D $\geq$ 100 for the day, evaluate key factor #2. Apply the same aggregated approach for the other identified days. If Q/D is < 100, then the Tier 2 approach is not appropriate. Show all calculations and values. The demonstration should clearly describe the result of the calculation, and the emissions, distance, and any assumptions that the air agency made in developing the Q/D ratio.

Key Factor #2 – Comparison of the event related O_3 concentration with non-event related high O_3 concentrations: The second key factor for a Tier 2 demonstration considers the characteristics of the event-related concentration versus the non-event O_3 concentration distribution at the monitor. Addressing key factor #2 involves showing that the exceedance due to the exceptional event:

- is in the 99th or higher percentile of the 5-year distribution of O_3 monitoring data, OR
- is one of the four highest O_3 concentrations within 1 year (among those concentrations that have not already been excluded under the EER, if any).

Applying this key factor recognizes that an air agency will likely need more detailed information to establish a clear causal relationship between the event and the monitored exceedance in an area or season with elevated non-event related O_3 concentrations. Therefore, limiting the Tier 2 demonstration to events in the 99th or higher percentile of 5 years of monitoring data will generally ensure the event-impacted data are high compared to other data at the monitoring site. If event-related concentrations have already been excluded for this year, then those values should not be included when determining the ranking. However, if the non-event O_3 concentrations at a monitor in the year (or season) when the event-related O_3 exceedance occurred are low when compared with other surrounding years in the 5 year record, an exceedance in this "low" O_3 year could still affect design value calculations and determinations within the scope of the EER. Therefore, if the data requested for exclusion are one of the fourth highest within 1 year (among those concentrations that have not already been excluded under the EER, if any), the key factor would be met. If both key factors (#1 and #2) are met, then a Tier 2 demonstration may be sufficient.

Compare the event-related O_3 concentration with non-event related high O_3 concentrations:

1) Provide the percentile ranking of the data requested for exclusion when compared with the most recent 5 years of monitoring data. Include the plot showing this result or reference the generated plot in another section of the demonstration.

2) If data are in the 99th (or higher) percentile OR are one of the top four O_3 maximums within 1 year AND key factor #1 is satisfied AND the EPA Regional Office and the affected air agency have discussed the potential event THEN the air agency should prepare a Tier 2 demonstration.

3.5.2 Evidence that the Fire Emissions Affected the Monitor(s)

In addition to the evidence suggested in Section 3.5.1, the air agency should supply at least **one piece** of additional evidence to support the weight of evidence that the emissions from the fire affected the monitored O_3 concentration. The example evidence explained below can be used by air agencies to demonstrate the fire emissions were present at the altitude of the monitor(s).

This evidence could include any of the following:

1) Photographic evidence of ground-level smoke at the monitor

2) Concentrations of supporting measurements [CO, PM (mass or speciation), VOCs, or altered pollutant ratios]

3) Evidence of changes in spatial/temporal patterns of O_3 and/or NOx.

While fires generate emissions of CO, NO, NO_2, VOCs, PM_{10}, and $PM_{2.5}$, anthropogenic sources, such as from industrial and vehicular combustion, also emit these pollutants. Therefore, the air agency should distinguish the difference in the non-event pollutant behavior (*e.g.*, concentration, timing, ratios, and/or spatial patterns) from the behavior during the event impact to more clearly show that the emissions from the fire(s) affected the monitor(s).
Specific analyses to support the above-identified evidence include the following:

- Photographic evidence of ground-level smoke at the monitor.

- Satellite evidence of smoke or precursors (NOx) at the monitoring site. *http://ofmpub.epa.gov/rsig/rsigserver?index.html* and *http://arset.gsfc.nasa.gov/airquality/applications/fires-and-smoke* may be helpful resources.

  Plots of co-located or nearby CO, $PM_{2.5}$, PM_{10}, or O_3 and $PM_{2.5}$ precursor concentrations in the same airshed (or nonattainment/near nonattainment area) that have increases or differences in typical behavior that indicate the fire's emissions impacted the monitor. Elevated levels of CO or PM (including pre-cursors) at an affected O_3 monitor upwind of urban centers or occurring at non-commute times at a monitor within an urban area despite the lack of a surface inversion would be consistent with fire plume impact. Include an explanation of the plots.

- Elevated light extinction measurements at or near the O_3 monitoring site that cannot be explained by emissions from other sources and are consistent with fire impact.

- The timing and spatial distribution of NO, NO_2, and O_3, shown with data from multiple monitoring sites. These pollutant concentrations may vary when influenced by a fire plume. Elevated levels that are widespread throughout a region, or are upwind of the urban area, may be due to impact of a fire plume. Peaks at locations and times different than those normally seen in an O_3 episode can indicate fire plume impact.

- Differences in CO:NOx ratios: The ratio of CO and NOx emissions depends on their source; for agricultural burning it is about 10-20, for wildfire and prescribe wildland burning about 100 (Dennis et al., 2002), whereas for high-temperature fossil fuel combustion sources it is more like 4 (Chin et al., 1994). Thus, an unusually high CO/NOx ratio is consistent with fire impact. Similarly, the CO/PM_{10} emission ratio is 8-16 in fires, but 200-2000 for vehicles (Phuleria et al., 2005). Changes in CO and CO ratios might be difficult to discern in an area dominated by vehicular CO, however, as the fire signal may be small in comparison.

- PM speciation data: $PM_{2.5}$ emissions from forest fires often contain elevated levels of organic carbon (OC) and occasionally are enriched in water soluble potassium (K) (Watson et al., 2001). Levoglucosan, a tracer molecule, is a constituent of smoke from biomass burning that can serve as an indicator for fire; PM_{10} from wood smoke is 14% or higher levoglucosan by mass (Jordan et al., 2006; Dennis et al., 2002). Co-located or nearby particle speciation data (OC, K, and/or levoglucosan) can be used to indicate fire impacts.

3.5.3 Evidence the Fire's Emissions were Transported to the Monitor

In addition to the evidence suggested in Sections 3.5.1 and 3.5.2, an air agency should provide evidence showing the emissions from the fire were transported to the monitor location (*i.e.,* the latitude and longitude). Air agencies can use either a trajectory analysis or a combination of satellite and surface measurements to show this transport. (These recommendations are the same as for Tier 1 demonstrations in Section 3.4.2, but are explained here again for completeness).

- *Trajectory analysis.* Atmospheric trajectory models use meteorological data and mathematical equations to simulate three-dimensional transport in the atmosphere. Generally, these models calculate the position of particles or parcels of air with time based on meteorological data such as wind speed and direction, temperature, humidity, and pressure. Model results depend on the spatial and temporal resolution of the atmospheric data used and also on the complexity of the model itself. The HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) model is frequently used to produce trajectories for assessments associated with air quality programs. HYSPLIT contains models for trajectory, dispersion and deposition. However, analyses applicable to exceptional events demonstrations typically use the trajectory component. The trajectory model, which uses existing meteorological forecast fields from regional or

global models to compute advection (*i.e.*, the rate of change of an atmospheric property caused by the horizontal movement of air) and stability, is designed to support a wide range of simulations related to the atmospheric transport of pollutants.

Air agencies can produce HYSPLIT trajectories for various combinations of time, locations and plume rise. HYSPLIT back-trajectories generated for specific monitor locations for days of high O_3 concentrations illustrate the *potential* source region for the air parcel that affected the monitor on the day of the high concentration and provide a useful tool for identifying meteorological patterns associated with monitored exceedances. HYSPLIT trajectories alone cannot definitively conclude that a particular region contributed to high pollutant concentrations, but a set of HYSPLIT trajectories that show no wind flow from a particular region on days with high concentrations might support discounting that region as contributing to the concentrations.

Air agencies could use other trajectory models, such as FLEXPART to demonstrate expected transport. Appendix A3 contains additional information on trajectory analyses.

- *Satellite Imagery of Plume with Evidence of the Plume Impacting the Ground.* Because plume elevation is not directly available from simple imagery, plume imagery alone does not conclusively show that fire emissions transported aloft reached a ground-level monitor. If plume arrival at a given location coincides with elevation of fire plume components (such as $PM_{2.5}$, CO or organic and elemental carbon) those two pieces of evidence combined can show that smoke was transported to the event location.

3.5.4 Summary of Evidence that Could be Used to Meet the EER Elements for Tier 1 and Tier 2 Demonstrations

Table 2 summarizes the technical support that air agencies can use to support the clear causal relationship in a Tier 2 demonstration, compared with a Tier 1 demonstration.

Table 2. Clear Causal Relationship Technical Demonstration Components Recommended for Tier 1 and Tier 2 Demonstrations

Tier 1 Demonstration Should Include	Tier 2 Demonstration Should Include
Comparison of the fire-influenced exceedance with historical concentrations	Comparison of the fire-influenced exceedance with historical concentrations
Evidence that the fire and monitor(s) meet the key factor	Evidence that the fire and monitor(s) meet the key factors (#1 and #2)
Evidence of transport of fire emissions from fire to the monitor (**one** of these): • Trajectories linking fire with the monitor (forward and backward), considering height of trajectories • Satellite evidence in combination with surface measurements	Evidence of transport of fire emissions from fire to the monitor (**one** of these): • Trajectories linking fire with the monitor (forward and backward), considering height of trajectories • Satellite evidence in combination with surface measurements

	Evidence that the fire emissions affected the monitor (**one** of these): • Visibility impacts (satellite or photo) • Changes in supporting measurements • Satellite NOx enhancements • Differences in spatial/temporal patterns

3.6 Additional Clear Causal Relationship Evidence for Tier 3 Events

As discussed in Section 3.3, air agencies may need additional detail to satisfy the clear causal relationship element for events not meeting the Tier 1 or Tier 2 key factors. This section describes the additional evidence for these Tier 3 event demonstrations.

3.6.1 Relationship of the Event, Monitor(s), and Exceedance to the Key Factors for Tier 2 demonstrations

As part of the weight of evidence showing for the clear causal relationship rule element, explain how the events, monitor and exceedance compare with the key factors outlined in Section 3.5.1. The relationship of the event to the Tier 2 key factors may help inform the amount of additional information that will be needed in a Tier 3 demonstration.

3.6.2 Evidence that the Fire Emissions Affected the Monitor(s)

Because the relationship between the fire-related emissions and the monitored exceedance or violation cannot clearly be shown using the Tier 1 or Tier 2 approach, air agencies will need additional evidence to show that the fire emissions affected the monitor. The clear causal relationship approach for Tier 3 demonstrations could include multiple analyses from those examples listed in Section 3.6.4. The example evidence suggested in Section 3.6.4 can be used by air agencies to demonstrate the fire emissions were present at the altitude of the monitor(s). Each additional piece of information that supports the event's influence will strengthen the air agency's position.

3.6.3 Evidence that the Fire Emissions were Transported to the Monitor

To demonstrate a clear causal relationship between the event's emissions and the monitored O_3 exceedance, air agencies should provide evidence showing that the emissions from the fire were clearly transported to the monitor. This will likely require a trajectory analysis similar to that described in Section 3.1.1 or the satellite plume analysis of Section 3.5.3.

Because the uncertainty of trajectory analyses increases with transport distance, frontal passages, and complex wind/terrain issues, additional information, such as analyses of surface meteorology (wind speed and direction), will further support the clear causal relationship rule element.

3.6.4 Additional Evidence that the Fire Emissions Caused the O_3 Exceedance

Depending on evidence supplied in other sections of the demonstration, an air agency may need some of the additional evidence listed here to demonstrate that the fire emissions caused the O_3 exceedance. Matching day analyses, statistical regression models, or photochemical models may help support the position that the emissions from the fire caused the O_3 exceedance.

- Comparison of O_3 Concentrations on Meteorologically Similar Days (Matching Day Analysis)
  O_3 formation and transport are highly dependent upon meteorology, therefore a comparison between O_3 on meteorologically similar days with and without fire impacts could support a clear causal relationship between the fire and the monitored concentration. Both O_3 concentrations and diurnal behaviors on days with similar meteorological conditions can be useful to compare with days believed to have been impacted by fire. Since similar meteorological days are likely to have similar O_3 concentrations, significant differences in O_3 concentrations among days with similar meteorology may indicate influences from non-typical sources.

  Meteorological variables to include in a similar day (or "matching day") analysis should be based on the parameters that are known to strongly affect O_3 concentrations in the vicinity of the monitor location. These variables could include: daily high temperature, hourly temperature, surface wind speed and direction, upper air temperature and pressure [such as 850 or 500 millibar (mb) height], relative or absolute humidity, atmospheric stability, cloud cover, and others as appropriate. Camalier et al. (2007) identifies and describes potentially useful parameters. These parameters should be matched within an appropriate tolerance. Since high O_3 days may be relatively rare, air agencies should examine several years of data for similar meteorology versus restricting the analysis to high O_3 days only. The complete range of normal expected O_3 on similar meteorology days will have value in the demonstration. A similar day analysis of this type, when combined with a comparison of the qualitative description of the synoptic scale weather pattern (*e.g.*, cold front location, high pressure system location), can show that the fire contributed to the elevated O_3 concentrations. Air agencies may also want to consider non-meteorological factors such as choosing days with similar, non-event emissions (possibly avoiding holidays and special public events, weekend versus weekend mismatches, and other days with unusual emissions). In a recently submitted demonstration,[1] the state of Kansas included an analysis showing the synoptic-scale weather pattern typing along with an evaluation of basic meteorological parameters similar to the "Matching Days" analysis described here.

- Statistical Regression Modeling
  Air agencies can use O_3 predictions from regression equations to assess fire's contribution to O_3 concentrations. Regression is a statistical method for describing relationships among variables. For estimating air quality concentrations, regression

[1] Available at: *http://www2.epa.gov/sites/production/files/2015-05/documents/kdhe_exevents_final_042011.pdf.*

equations are developed to describe the relationship between pollutant concentrations (referred to as the prediction, what is being predicted) and primarily meteorological variables (referred to as the predictors). Because regression equations are developed with several years of data, they represent the relationship between air quality and meteorology under typical emission patterns; even if some historical exceptional events data are included in the development, the influence of those days will likely be small on the developed model provided there are far more typical days than event-related days. Therefore, the difference between the predictions and observations can provide a reasonable estimate of the air pollution caused by event-related emissions (*e.g.*, emissions from fires) provided the analysis accounts for the typical remaining variance of typical days (variability in monitored data not predicted by the model).

Air agencies can develop the regression equation using the O_3 data for the monitor(s) under investigation and meteorology data from the closest nearby National Weather Service station. A small subset of the data should be reserved for testing the regression equation. Once a regression equation has been properly developed and tested, it can be used to predict the daily maximum O_3 values. The differences between the predicted values and the measured values are analyzed, and the 95th percentile of those positive differences (observed O_3 is greater than predicted) is recorded. This 95 percent error bound is added to the O_3 value predicted by the regression equation for the flagged days, and any difference between this sum and the observed O_3 for the flagged day may be considered an estimate of the O_3 contribution from the fire if evaluation of the top 5th percentile shows similar O_3 days in the absence of smoke are rare or not observed.

Users of regression models should consider the uncertainties in the model's prediction abilities, specifically at high concentrations, before making conclusions based on the modeled results. A key question when considering model uncertainty is whether the model predicts O_3 both higher and lower than monitored values at high concentrations (above 65 or 70 ppb) or whether the model displays systematic bias on these high monitored days?

The limitations of the regression equation itself defines the limitations of this method. This approach is more rigorous than a comparison to similar meteorological days in that it considers the relationship between meteorological parameters, but regression is less rigorous than air quality modeling, which employs more parameters and more physical processes in its calculations. While statistical modeling does not resolve all the complexities of the atmosphere, carefully crafted regression models can provide an estimate of contribution to support the clear causal relationship portion of an exceptional events demonstration. There are several methods for developing a regression equation to estimate O_3 concentrations from meteorological variables (Camalier et al., 2007; STI, 2014).[2]

- Photochemical modeling
  This section describes the air quality modeling tools best suited for estimating fire emissions impacts in demonstrations needing a more refined assessment. Secondary

[2] Camalier et al., 2007, Atmos. Environ. and STI Technical Report STI-910507-6062, 9/5/14.

pollutant impacts such as O_3 and $PM_{2.5}$ need to be assessed at various spatial scales (near-source and long-range transport) for a variety of regulatory programs. Modeling systems used for these assessments should be appropriate for this purpose and should be evaluated for skill in replicating meteorology and atmospheric chemical and physical processes that result in secondary pollutant formation and deposition. Photochemical grid models treat emissions, atmospheric chemistry, and physical processes such as deposition and transport. These types of models are appropriate for assessment of near-field and regional scale reactive pollutant impacts from specific industrial sources (Baker and Foley, 2011; Bergin et al., 2008; Kelly et al., 2015; Zhou et al., 2012), specific fire events (Kansas Department of Health and Environment, 2012) or all sources (Chen et al., 2014; Russell, 2008; Tesche et al., 2006). Photochemical transport models have been used extensively to support State Implementation Plans and explore relationships between inputs and air quality impacts in the United States and beyond (Cai et al., 2011; Hogrefe et al., 2011; Russell, 2008; Tesche et al., 2006). Several state of the science photochemical grid models could be used to estimate fire impacts including (but not limited to) the CAMx (*www.camx.com*), CMAQ (*https://www.cmascenter.org/cmaq/*), and WRF-CHEM (*https://www2.acd.ucar.edu/wrf-chem*) models. These models have been used to estimate fire contribution to O_3 in the past (Fann et al., 2013; Jiang et al., 2012; Kansas Department of Health and Environment, 2012; Kwok et al., 2015; U.S. Environmental Protection Agency, 2014). Predictions of fire impacts on air quality are complex due to uncertainties in emissions, height of emissions, plume temperature, and plume chemistry (including radiative impacts on chemistry). However, with proper set-up, application, and evaluation, air quality models can be used to indicate fire impacts on O_3 concentrations. Model evaluation of predictive skill on both event days, both for concentration and spatial extent of impacts, and for typical days with little or no exceptional precursor levels is key to using the model results in a demonstration.

Where set up appropriately, photochemical grid models could be used with a variety of approaches to estimate and assess the contribution of single sources to primary and secondarily formed pollutants. These approaches generally fall into the category of source sensitivity (how air quality changes due to changes in emissions) and source apportionment (what air quality impacts are related to certain emissions). The simplest source sensitivity approach (brute-force change to emissions) is to simulate two sets of conditions, one with all emissions and one with the source of interest removed from the simulation (Cohan and Napelenok, 2011). The difference between these simulations provides an estimate of the air quality change related to the change in emissions from the fire event (Kansas Department of Health and Environment, 2012). Another source sensitivity approach to differentiate the impacts of fire events on changes in model predicted air quality is the direct decoupled method (DDM), which tracks the sensitivity of an emissions source through all chemical and physical processes in the modeling system (Dunker et al., 2002). Sensitivity coefficients relating source emissions to air quality are estimated during the model simulation and output at the resolution of the host model.

Some photochemical models have been instrumented with source apportionment, which tracks emissions from specific sources through chemical transformation, transport, and deposition processes to estimate a contribution to predicted air quality at downwind

receptors (Kwok et al., 2015; Kwok et al., 2013). Source apportionment has been used to differentiate the contribution from specific sources on model predicted O_3 and $PM_{2.5}$ (Baker and Foley, 2011; Baker and Kelly, 2014). The DDM has also been used to estimate O_3 and $PM_{2.5}$ impacts from specific sources (Baker and Kelly, 2014; Bergin et al., 2008; Kelly et al., 2015) as well as the simpler brute-force sensitivity approach (Baker and Kelly, 2014; Bergin et al., 2008; Kelly et al., 2015; Zhou et al., 2012). Limited comparison of specific source impacts between models and approaches to differentiate single source impacts (Baker and Kelly, 2014; Kelly et al., 2015) show generally similar downwind spatial gradients and impacts.

Air agencies should verify the modeled estimates of fire events with other sources of information such as satellite products and ground based measurements and not use the model as the sole evidence supporting the fire event contribution. Significant variation in the modeled result from other information sources may indicate that the photochemical model predictions are unreliable for demonstration purposes.

3.7 Example Conclusion Statement

Air agencies should provide the supporting evidence and analyses identified in Sections 3.1-3.6 of this guidance to document the clear causal relationship between the fire event and the monitored O_3 exceedance or violation and conclude the analysis with a statement similar to the language below:

"Based on the evidence, including comparisons and analyses, provided in [section X] of this demonstration, the fire events, which occurred on [dates] in [location] and the monitored O_3 exceedance on [dates/time of data requested for exclusion, or reference to summary table in demonstration] were established to have a clear causal relationship. The clear causal relationship evidence also demonstrates that the event affected air quality at the monitor.

Appendix A2. Relating Fire Emissions and Downwind Impacts

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Summary

To understand general relationships between the magnitude of fire emissions and potential downwind O_3 impacts, the EPA conducted an assessment of fire case studies. These case studies were drawn from peer-reviewed literature, EPA-approved exceptional events demonstrations for fires that influenced O_3 concentrations, and EPA-performed photochemical modeling studies. The dependence of O_3 impacts on fire emissions and distance from the fire across these case studies has been compared to determine fire characteristics that are expected to lead to meaningful O_3 impacts.

Background

Fires can impact O_3 concentrations by emitting known O_3 precursors including NO_X and VOCs. These precursor emissions can generate O_3 within the fire plume or can mix with emissions from other sources to generate O_3 (Jaffe and Wigder, 2012). Also, in some situations, including near fires, reduced O_3 concentrations have been observed and attributed to O_3 titration by enhanced NO concentrations and reduced solar radiation available to drive photochemical reactions (Jaffe et al., 2008; Yokelson et al, 2003). The magnitude and ratios of emissions from fires vary greatly depending on fire size, fuel characteristics, and meteorological conditions (Akagi et al., 2012). As a result of variable emissions, radiative impacts, and non-linear O_3 production chemistry, the O_3 production from fires is very complex, highly variable, and often difficult to predict (Jaffe and Wigder, 2012). Understanding and predicting O_3 formation from fires remains an active area of research.

Despite the complexities in predicting O_3 formation from fire emissions, several studies have found enhancements in O_3 concentrations attributable to fire impacts. For example, Pfister et al. analyzed surface O_3 data during a high fire year in California (2007) with modeled fire impacts and found 8-hour O_3 concentrations were approximately 10 ppb higher when the modeled impacts were high (Pfister et al., 2008). Jaffe et al. analyzed three specific fire periods in the western US during 2008 and 2012, and compared surface O_3 concentrations with two different modeled estimates of fire contributions to O_3 concentrations to find enhancements in O_3 when fire impacts were predicted to be high (Jaffe et al., 2013).

Previously Approved Fire-Impacted O_3 Exceptional Events Demonstrations

The EPA's EER (CFR parts 50 and 51 codified at 50.1, 50.14 and 51.930) allows air agencies to exclude air quality data that has been influenced by an exceptional event, once the agency has submitted and the EPA has approved a demonstration satisfying the EER elements. Many events, including fires, qualify for consideration under the EER.

Between 2010 and August 2015, the EPA approved two exceptional events demonstrations that linked monitored O_3 exceedances to fire impacts. The first was approved in 2011. In this case, the EPA concurred on three exceedances of the 1-hour O_3 NAAQS near Sacramento, California in 2008 due to a series of lightning-initiated wildfires throughout northern California. The second demonstration for fire impact on O_3 was approved in 2012. In this case, the EPA concurred with the exclusion of eight MDA8 exceedances during April 2011 in Kansas due to impacts from prescribed fires and wildfires. Both of these demonstrations are available at *http://www2.epa.gov/air-quality-analysis/exceptional-events-submissions-table*.

Assessments of Q/D Relationships from Previously Approved Demonstrations and Relevant Peer-Reviewed Literature

At least one air quality related program (*i.e.*, determining impacts at Class I areas) uses an emissions divided by distance (Q/D) key factor as a screening tool. The EPA believes that it is appropriate to use a similar approach, along with additional information about the fire event, to determine whether a simpler and less resource-consuming exceptional events demonstration provides sufficient evidence to satisfy the clear causal relationship criteria of the EER for fire O_3 demonstrations.

To determine whether a relationship existed between approved demonstrations and Q/D values, the EPA estimated Q/D values from previously approved, fire-related O_3 exceptional events demonstrations. The EPA also included in this comparison, the results from one peer-reviewed publication, which included sufficient detail for a similar analysis (Jaffe et al., 2013). The EPA used daily fire emissions estimates from the 2008 (*ftp://ftp.epa.gov/EmisInventory/fires/*) and 2011 (*http://www3.epa.gov/ttnchie1/net/2011inventory.html*) NEIs to estimate Q from fires impacting the O_3 monitors. For consistency, the EPA also used NEI-based estimates for the Jaffe et al. fires. In determining the appropriate emissions to use in this assessment, the EPA summed NO_X and rVOC because both are precursors for O_3 formation. The NEI reports total organic gas (TOG) so the reactive fraction of these emissions (rVOC) was estimated by applying the fraction of reactive gas to total organic gas based on speciation profiles for fires provided by the SPECIATE database. A factor of 0.6 was selected based on the SPECIATE database profile used by CMAQ for fires (speciation profile number 5560).[3]

Fire events included in the estimated Q values were based on the sum of emissions from only some of the events listed by the relevant air agencies in the demonstrations because the demonstrations included fires that may not directly impact the monitor. The CARB exceptional events demonstration identified all wildfires burning in California during the time period of the O_3 exceedances, and a subset of those (within state of CA, with latitude north of 37N (~north of Santa Cruz) and longitude west of -119W (~west of Mono Lake) were used. The Jaffe et al., article assessed the impact of the 2008 Northern California fires in Reno, NV (versus at California monitors). The same fire subset was used for the Jaffe et al. analysis as for the CARB demonstration. For the Kansas Department of Health and Environment demonstration, the EPA included all fire events labeled as "Flint Hills" in the NEI emissions file. Emissions totals within these bounds on the day of the O_3 exceedances were used to calculate emissions totals, Q. The

[3] SPECIATE is the EPA's repository of volatile organic gas and particulate matter speciation profiles of air pollution sources. Available at *http://www3.epa.gov/ttnchie1/software/speciate/*.

uncertainty in Q was taken to be approximately ±25% and was taken from the differences between the NO_X estimates from the NEI and the NOx estimates from the Fire Inventory from NCAR (FINN) emissions inventories of all fires (Wiedinmyer et al., 2011).

O_3 impacts were determined differently by the CARB demonstration, the KDHE demonstration, and the Jaffe et al. article. The CARB demonstration used a statistical regression model to estimate fire contributions to O_3 concentrations. The KDHE demonstration used both a matching day analysis and photochemical modeling to estimate O_3 impacts. The Jaffe et al. paper used both photochemical and statistical residual modeling to estimate O_3 impacts.

A summary of the fire impacts on O_3 compared with Q/D for the approved demonstrations and the Jaffe et al. article is shown in Figure A2-1. Distance (km) between the fire and the O_3 monitors was calculated based on an average fire location determined with an emissions-weighted fire center. The uncertainty range in D was determined by using the maximum distance between the monitor and a fire event (within the subset given above) on the day of the exceedance. The range shown for the CARB O_3 impacts reflects the uncertainty analysis included in the demonstration. The ranges included for O_3 impacts estimated by the KDHE demonstration and the Jaffe et al. paper represent the range in estimates of O_3 impacts determined by the two different methods used in each case.

Modeling Studies of Wildfire Impacts on O_3

Some uncertainty exists in the magnitude of emissions estimates, VOC and $PM_{2.5}$ speciation of emissions, downwind transport, chemical reactions in fire plumes, and representation of important physical processes like reduced photolysis due to smoke. However, the emissions used as input to air quality models can be paired with estimated downwind O_3 contribution to assess screening level relationships between precursor emissions and downwind impact. Constructing these relationships is useful for planning purposes and making preliminary determinations about whether fires with emissions of a certain amount and distance away may impact a monitor and warrant further investigation for fire contribution using additional corroborative information.

The entire year of 2011 was applied using the CMAQ version 5.0.2 model (*www.cmascenter.org*). Meteorological input was generated using version 3.4.1 of the WRF prognostic meteorological model (Skamarock et al., 2008). Both modeling systems were applied using the same grid projection and model domain covering the continental United States with 12 km sized grid cells. Contributions from four specific fire events were tracked using source apportionment approaches. Source apportionment tracks primarily emitted and precursor emissions from specific fire events through the model's chemical and physical processes to track contribution to primary and secondarily formed pollutants. The integrated source apportionment approach has been implemented in CMAQ for O_3 (Kwok et al., 2015) and $PM_{2.5}$ (Kwok et al., 2013) and was used in this analysis to track the contribution from each fire event. CMAQ with source apportionment was applied for four different multi-day fire events in 2011: Wallow, Waterhole, Big Hill, and Flint Hills. The days included in each model simulation for each fire event and the daily total fire event emission estimates are shown in Table A2-1. Emissions-weighted fire event locations are shown in Table A2-2. All the emissions from each multi-day fire were tracked as a single source, so it is not possible to determine from the results how a single day of fire event emissions affects a single day of O_3 concentrations. For example, O_3

effects on the third day of a fire may be a contribution of direct effects from a same day plume and effects from recirculated VOC, NOx and O_3 from earlier days.

Wildfire and prescribed fire emissions were included when and where these emissions occur within the modeling domain. These emissions are based on the latest version of the SMARTFIRE system (*http://www.airfire.org/smartfire/*). Detailed information about how the EPA develops wildland fire inventories can be found in the 2011 NEI Technical Support Document (U.S. Environmental Protection Agency, 2014). This approach relies on a combination of satellite detection of fires merged with on-the-ground observational data where available. Ground-based observations and local fuel information are used whenever possible as these factors can have a large impact on the emissions. CMAQ currently uses one single speciation profile (5560; Table A2-3) to speciate TOG fire emissions into specific compounds (*e.g.*, toluene, benzene, etc.) that are subsequently used in the gas phase chemical mechanism within CMAQ. Similarly, a single profile is used to map total $PM_{2.5}$ emissions from fires to specific compounds (*e.g.*, elemental carbon, organic carbon, etc.). Daily total emissions for each fire event tracked for O_3 contribution are shown in Table A2-1. The EPA also conducted a sensitivity analysis including reducing each fire's emissions to half the original emissions.

Figure A2-2 shows maximum hourly (across all modeled days of the event) source apportionment based O_3 impacts from the fire events tracked in this assessment. Fire NO_X emissions tend to contribute more to O_3 formation than fire VOC emissions, on a per fire comparison basis, for the fire events in the western United States where biogenic VOC is often abundant (especially near these particular fire events). The stronger effect from NOx emissions compared to VOC emissions on a per ton basis (not shown) is even more pronounced, given the tonnage values in Table A2-1. The NO_X contribution could be favored in the model if O_3 formation was NO_X limited even when the contributing VOC was also from the same fire event. The fire event modeled in Kansas illustrates that VOC emissions from fires can also be important, especially when other VOC sources are less abundant.

Figure A2-3 depicts downwind O_3 and CO impacts. This figure also shows Q/D for these events and forward HYSPLIT trajectory endpoints (from each day included in Table A2-1) from release out to 48 hours. This figure clearly shows the importance of pairing information about the trajectory of fire emissions in combination with simple metrics of impact such as Q/D. The Wallow fire event had the most consistent trajectories across the days of the event. For the other fire events, wind directions on different days differed considerably.

Maximum hourly fire impacts on O_3 (that were greater than 1.0 ppb) and the corresponding distance of the grid cell where the maximum impact occurred from the emissions-weighted average location of the fire event are shown in Figure A2-4. The colored box represents the 25^{th}-75^{th} percentiles of the distribution of O_3 impacts larger than 1.0 ppb, and the solid line within the colored box indicates the median of the distribution. Impacts only up to 1000 km (for Wallow, Flint Hills, and Waterhole) and 550 km (for Waterhole and Big Hill) are shown since the magnitude of the O_3 impacts decrease at increased distances. The maximum O_3 impacts tend to be highest in closer proximity to the event and decrease as distance from the event increases (Figure A2-4). When these impacts are normalized by the sum of NOx+rVOC emissions for the event day with the highest emissions during the period modeled (Figure A2-5), the magnitude of O_3 impacts varies over the range of Q/D values, with larger O_3 impacts occurring at higher Q/D

values. The truncation of distances used in Figure A2-4 leads to the absence of O_3 impacts at low Q/D values (*e.g.*, ~20 for the Wallow Fire) in Figure A2-5.

The results shown in Figure A2-5 help determine the appropriateness of using the Q/D approach as one key factor in a simpler and less resource-consuming exceptional events demonstrations for certain fire events (*i.e.*, Tier 2). In the figure for each modeled fire event, modeled maximum O_3 impacts are shown for the first two days, except for the Big Hill Fire where the entire, three day event is shown. Each data point represents the maximum, hourly O_3 impact (over 1 ppb) that occurred in a grid cell during the first 48 hours of the event. In general, higher O_3 impacts are predicted at larger Q/D values. Comparisons across the four fire events modeled here indicate more and larger O_3 impacts at high Q/D values from the fires with the highest emissions (Wallow and Flint Hills) versus the smaller, lower emissions fires (Big Hill and Waterhole). When Q/D values from a fire event are paired with both elevated monitored O_3 concentrations (*i.e.*, Tier 2 key factor #2) and evidence (e.g., HYSPLIT trajectory or other analyses identified in sections 3.5.2 and 3.5.3) linking the affected monitor to the location(s) of the subject fire(s), the EPA believes that the Q/D relationship can be used to indicate when large O_3 impacts are expected to occur.

To examine the utility of the Q/D metric, Q/D was calculated for all fires in the National Emission Inventory for the years 2008 through 2013 to provide an aggregate context for areas and times where fires may be large contributors to elevated air quality. Figures A2-6 through A2-8 show the count of days with NO_X+rVOC Q/D values greater than 50, 100, and 200 for 2008 through 2013. These figures illustrate how the fire events modeled for this assessment from 2011 compare to other fires that year and to fires from other recent years where data are available. These results can be used to investigate how many days and areas would meet various thresholds for the Q/D key factor.

Conclusions

The fire event impacts estimated with the photochemical model CMAQ suggest both NO_X and VOC emissions from fire events can lead to downwind O_3 formation and the importance of these precursors varies among fires, most likely due to the surrounding environment's availability of NO_X and VOC emissions. Since information about the surrounding environment may not always be practically available, the approach for estimating fire impacts should be inclusive of both NO_X and reactive VOC emissions.

The downwind O_3 contribution from these fire events is greatest in the proximity of the fire and tends to gradually decrease as distance from the source increases. The spatial plots of downwind O_3 impacts show that the impacts occur in the direction of air mass movement from the fire event to specific places downwind. As indicated above, tiering approaches that do not explicitly account for pollutant transport (*e.g.*, Q/D) should be accompanied with information about pollutant transport from another source such as HYSPLIT trajectories to better spatially represent the downwind impacts.

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Table A2-1. Daily and emissions for each tracked fire event in 2011. rVOC is the sum of all VOC excluding methane and non-reactive species.

Fire Event	Month-Day	CO	NOX	rVOC	NOX+rVOC
Waterhole	822	9,441	96	1,331	1,427
Waterhole	823	17,652	171	2,487	2,658
Waterhole	824	38,086	408	5,373	5,780
Waterhole	825	637	6	90	96
Waterhole	826	34	1	5	6
Big Hill	814	243	7	35	42
Big Hill	815	3,248	92	468	560
Big Hill	816	189	5	27	33
Flint Hills	401	30,675	867	4,417	5,285
Flint Hills	402	51,555	1,413	7,417	8,830
Flint Hills	403	14,526	383	2,087	2,470
Flint Hills	404	3,744	106	539	646
Flint Hills	405	20,233	564	2,912	3,477
Flint Hills	406	78,622	2,218	11,321	13,539
Flint Hills	407	9,719	263	1,398	1,661
Flint Hills	408	59,020	1,584	8,485	10,070
Flint Hills	409	60,294	1,656	8,675	10,331
Flint Hills	410	9,194	257	1,324	1,580
Flint Hills	411	57,428	1,540	8,256	9,796
Flint Hills	412	105,636	2,950	15,206	18,157
Flint Hills	413	60,484	1,670	8,704	10,373
Flint Hills	414	7,874	215	1,133	1,348
Flint Hills	415	95	3	14	16
Wallow	604	115,438	1,516	16,331	17,847
Wallow	605	49,951	697	7,074	7,771
Wallow	606	113,160	1,509	16,013	17,522
Wallow	607	53,030	705	7,504	8,209
Wallow	608	131,675	1,774	18,636	20,409
Wallow	609	59,155	839	8,379	9,218
Wallow	610	52,127	736	7,383	8,119

Table A2-2. Emissions weighted fire event locations.

Fire Event	Latitude	Longitude
Waterhole	45.6141	-106.7889
Big Hill	42.5673	-115.8093
Flint Hills	37.9466	-96.3543
Wallow	33.8174	-109.3272

Table A2-3. Speciation profile (5560) used to map TOG emissions to specific lumped compound groups for photochemical model application.

Profile	Inventory	Model	Fraction
5560	TOG	UNR	0.22
5560	TOG	PAR	0.18
5560	TOG	CH4	0.18
5560	TOG	FORM	0.08
5560	TOG	MEOH	0.08
5560	TOG	OLE	0.07
5560	TOG	ALD2	0.05
5560	TOG	ETH	0.04
5560	TOG	TOL	0.03
5560	TOG	ALDX	0.02
5560	TOG	ETHA	0.02
5560	TOG	BENZENE	0.02
5560	TOG	TERP	0.01
5560	TOG	XYL	0.01
5560	TOG	IOLE	0.00
5560	TOG	ISOP	0.00
5560	TOG	ETOH	0.00

Figure A2-1. Summary of O_3 impacts versus Q/D relationships for approved demonstrations (CARB_Folsom_2008 and KDHE_FlintHills_2011) and impacts reported by Jaffe and Wigder (2012). No results from the EPA's photochemical modeling are shown in this Figure.

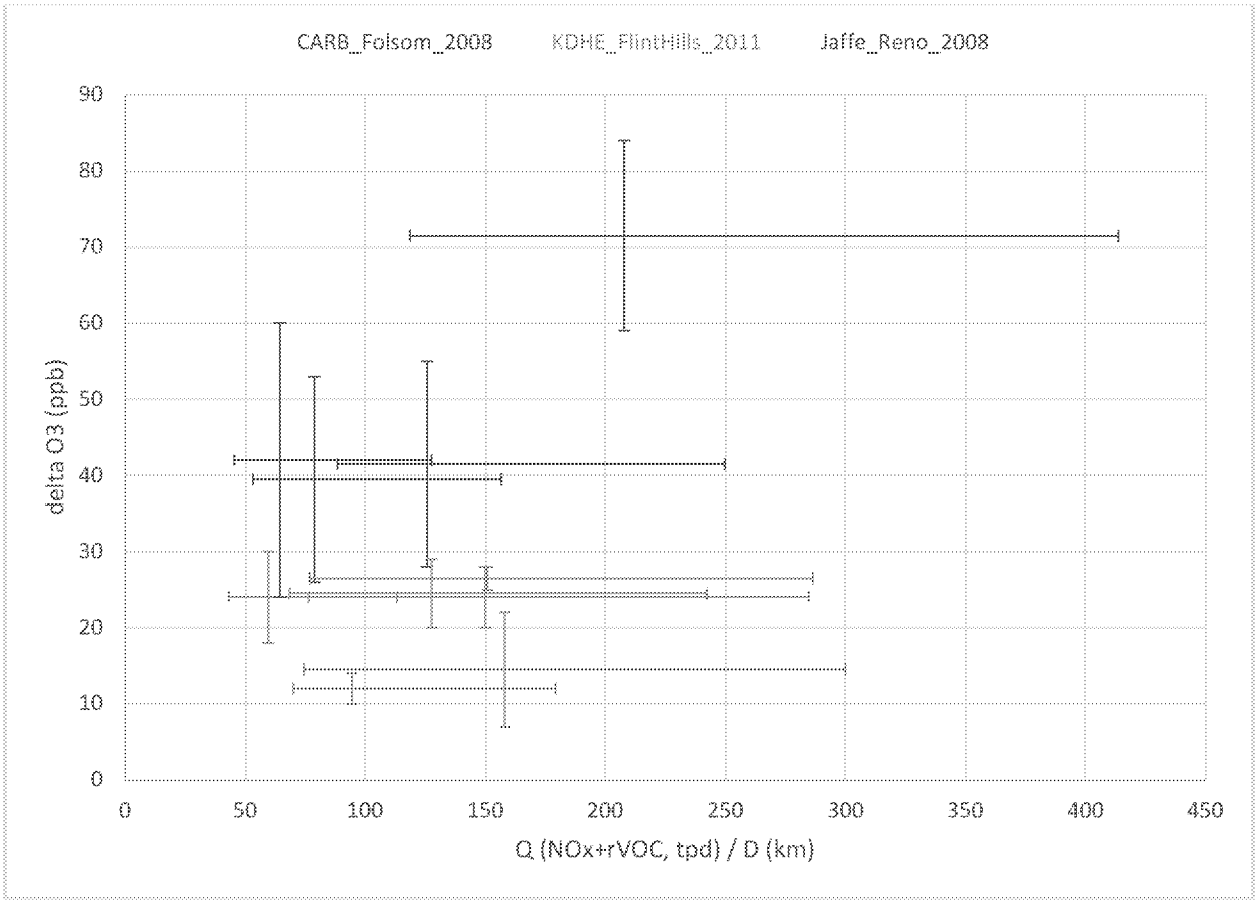


Figure A2-2. Event maximum 1-hour O_3 (ppb) impacts (left panels). The percent contribution from fire event NO_X emissions to event maximum 1-hour O_3 impacts shown at right. The percent contribution plots show that both NO_X and VOC emissions from fires can contribute to downwind O_3 formation.

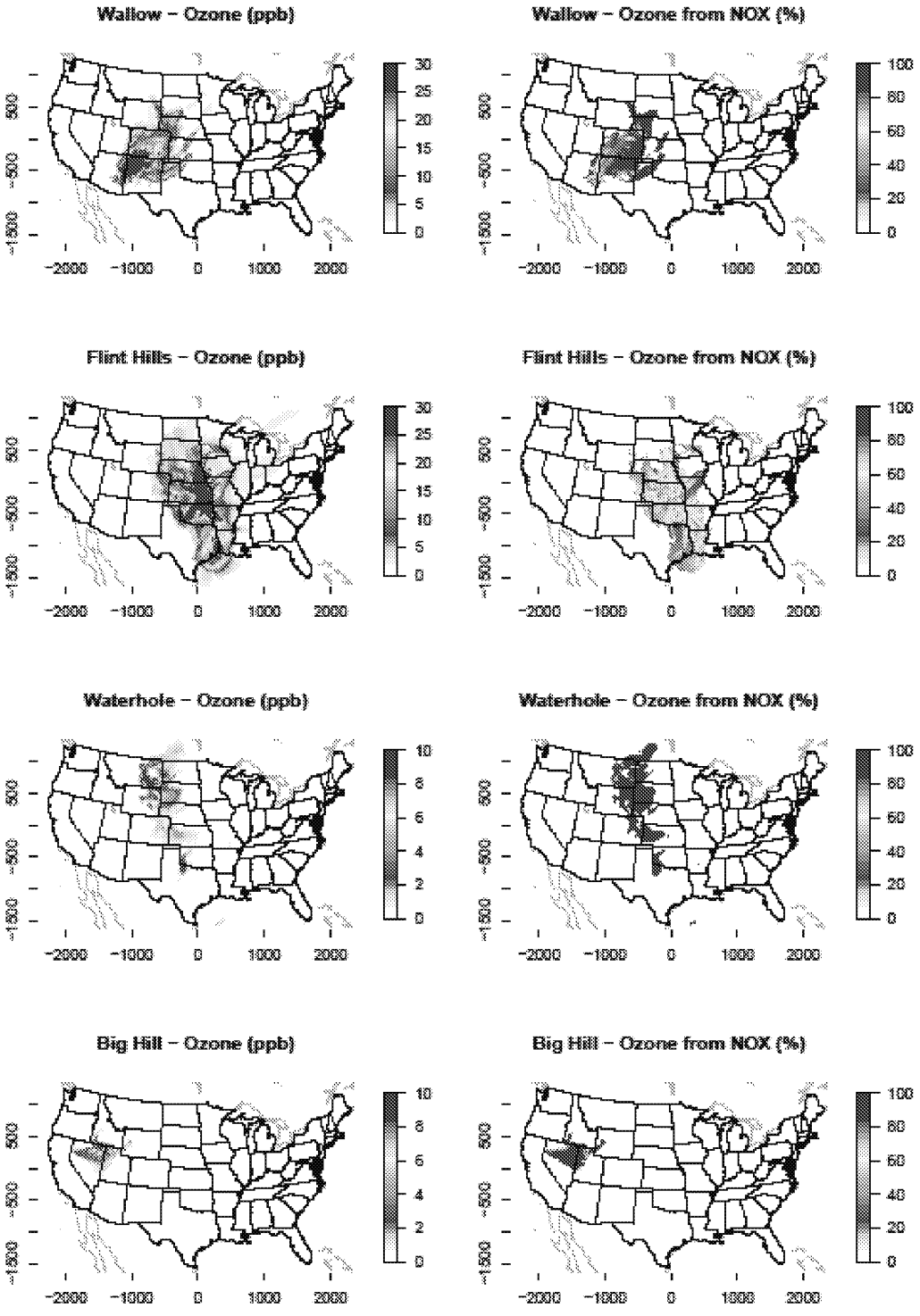


Figure A2-3. Event maximum 1-hour CO (left panels), O_3 (second to left panels), Q/D (second to right panels), and forward trajectories (right panels) shown for multiple fire events. Q/D is based on daily maximum NOX+rVOC emissions from the fire event during the period modeled. Forward trajectories are shaded by hours from release with warm colors (red and orange) representing hours during the first day and cooler colors the 2nd day (24 to 48 hours) from release.

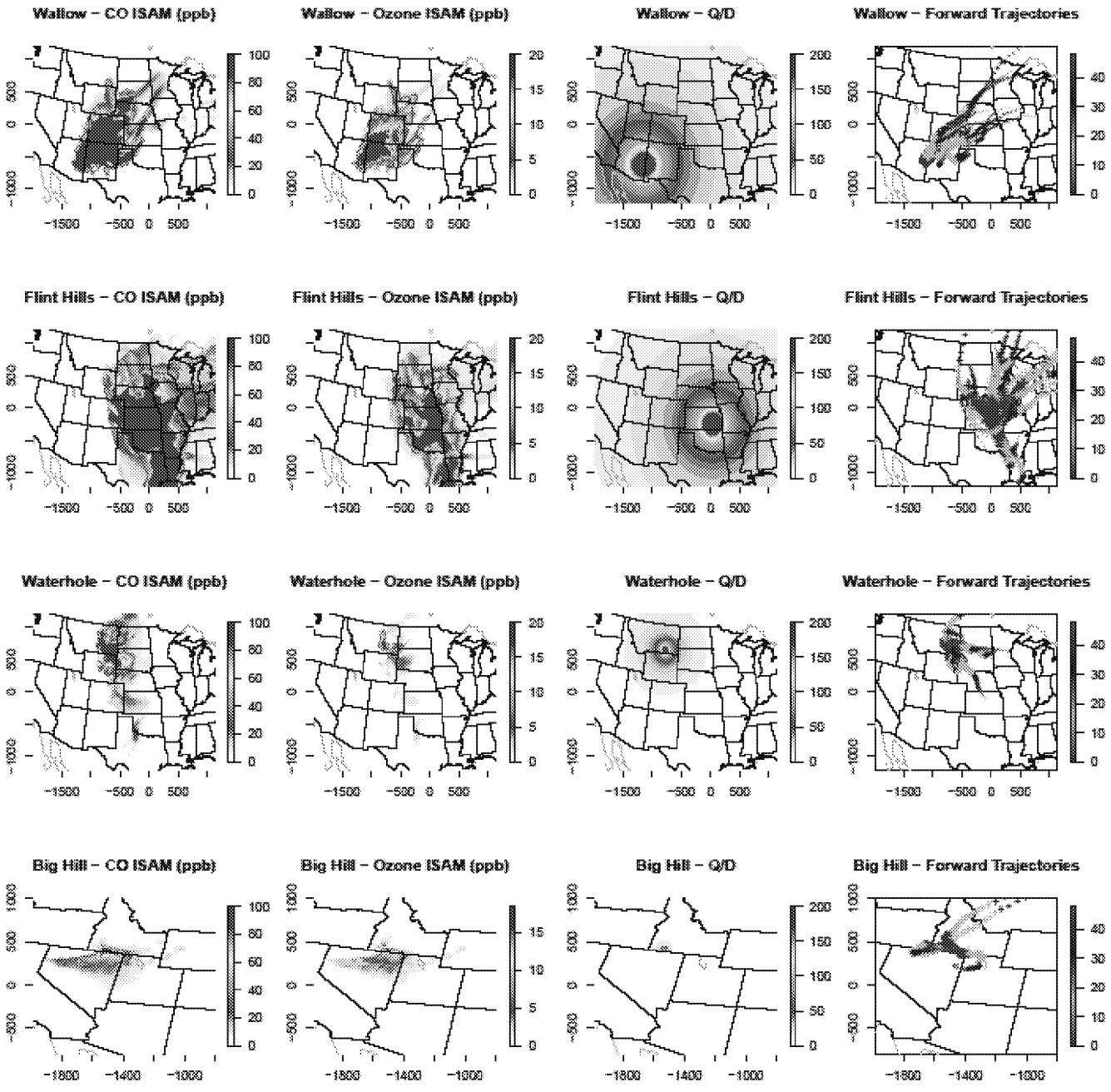


Figure A2-4. Distribution of hourly O_3 impacts from fire events by distance from the location of the fire event.

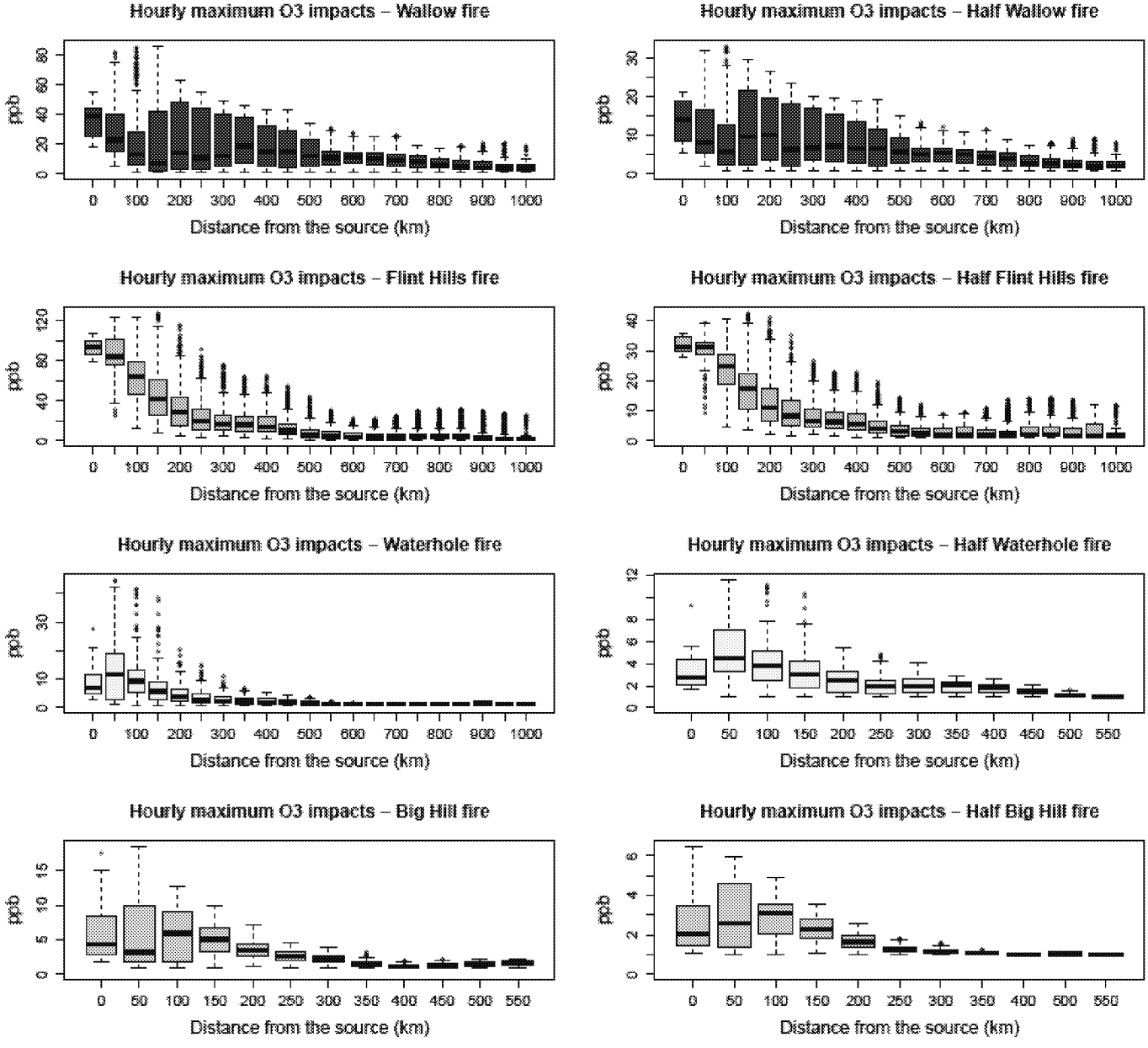


Figure A2-5. Hourly maximum O_3 impacts from the first two days of each fire event (Table A2-1) shown by Q/D. O_3 impacts only up to 1000 km from the fire have been included in this analysis.

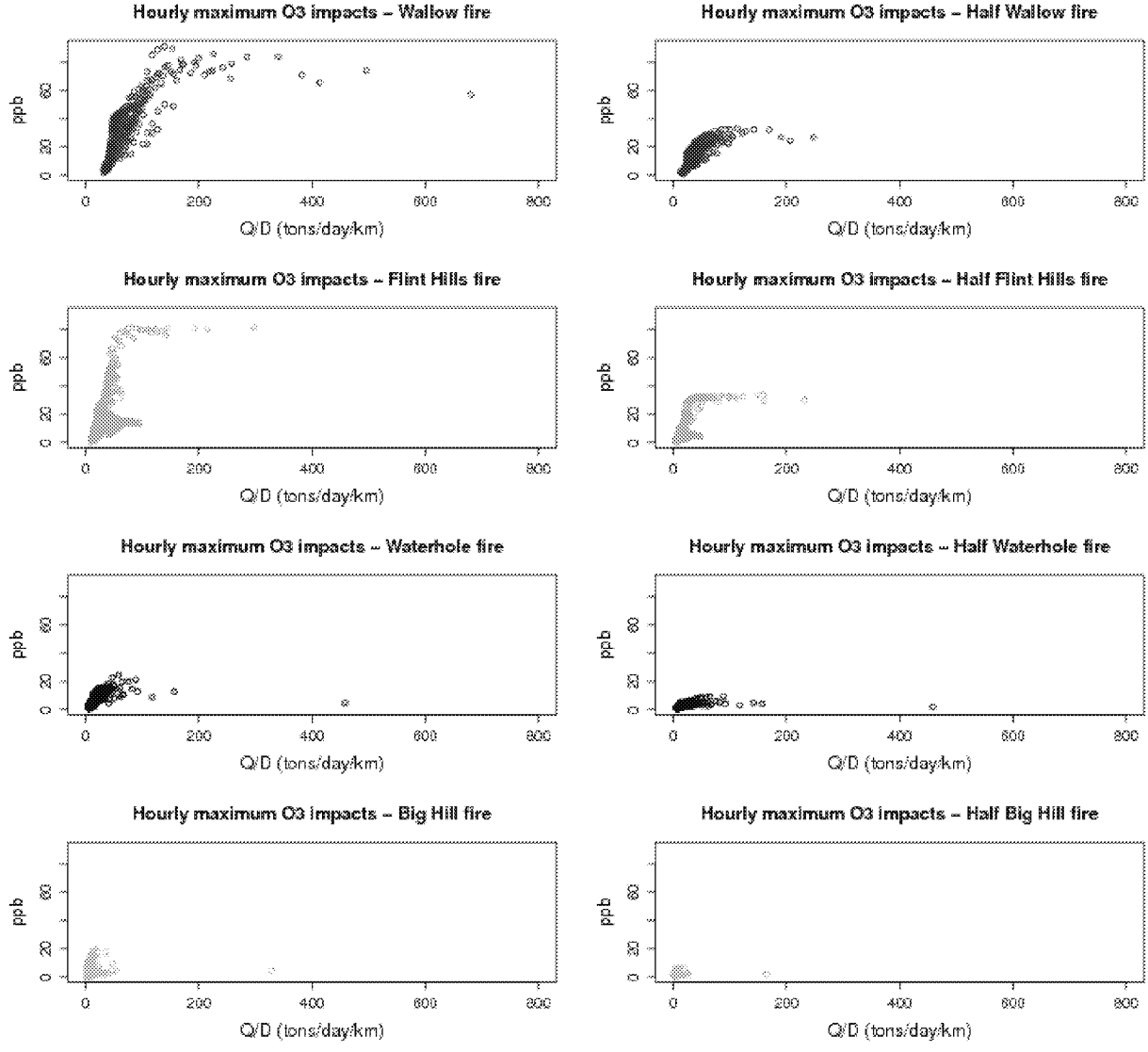


Figure A2-6. Count of days with NOx+rVOC Q/D > 50 for 2008 through 2013. Note scale has been capped at 10 to more easily distinguish the values below 10. Red may actually indicate 10 or greater than 10.

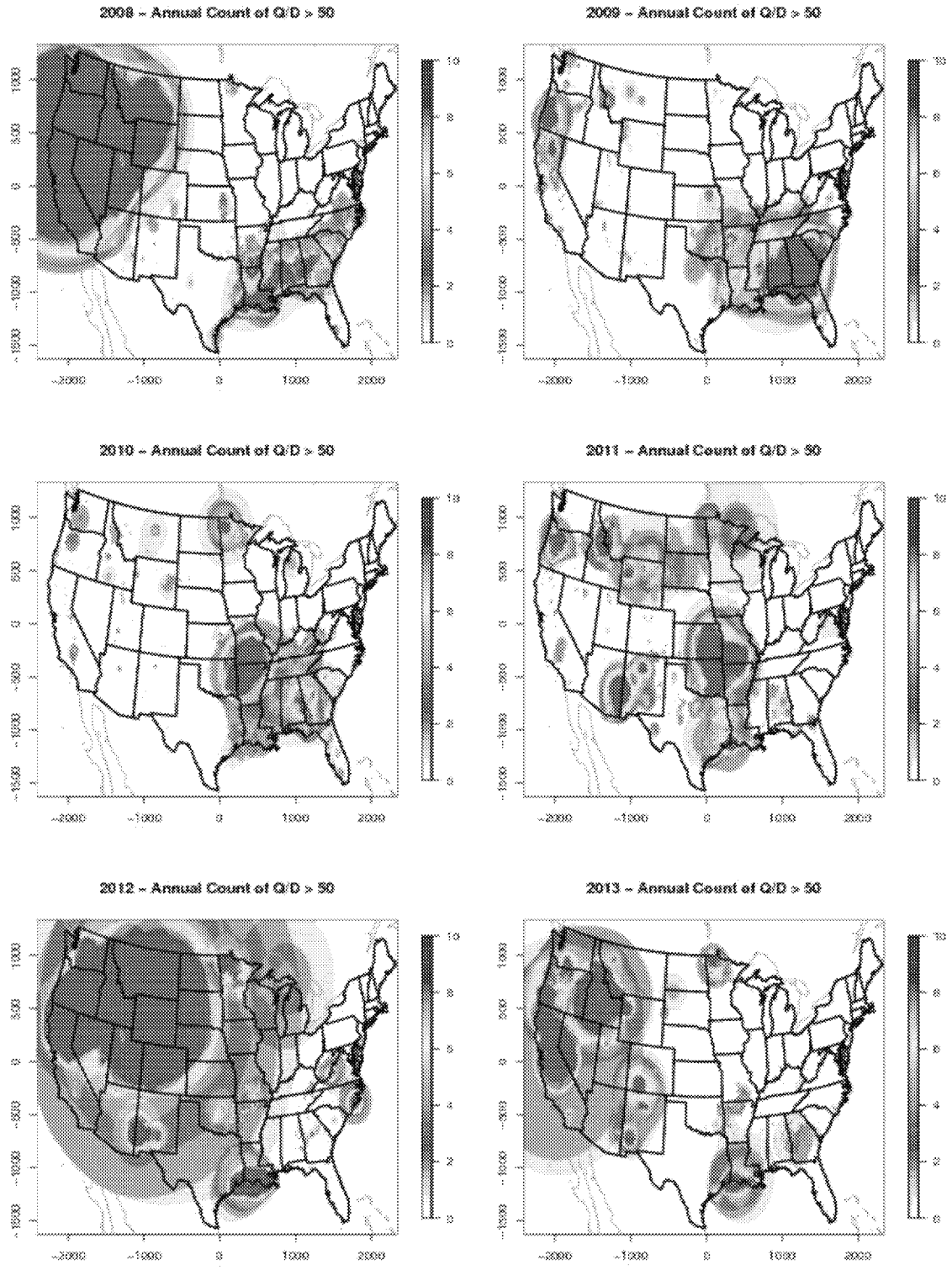


Figure A2-7. Count of days with NOx+rVOC Q/D > 100 for 2008 through 2013. Note scale has been capped at 10 to more easily distinguish the values below 10. Red may actually indicate 10 or greater than 10.

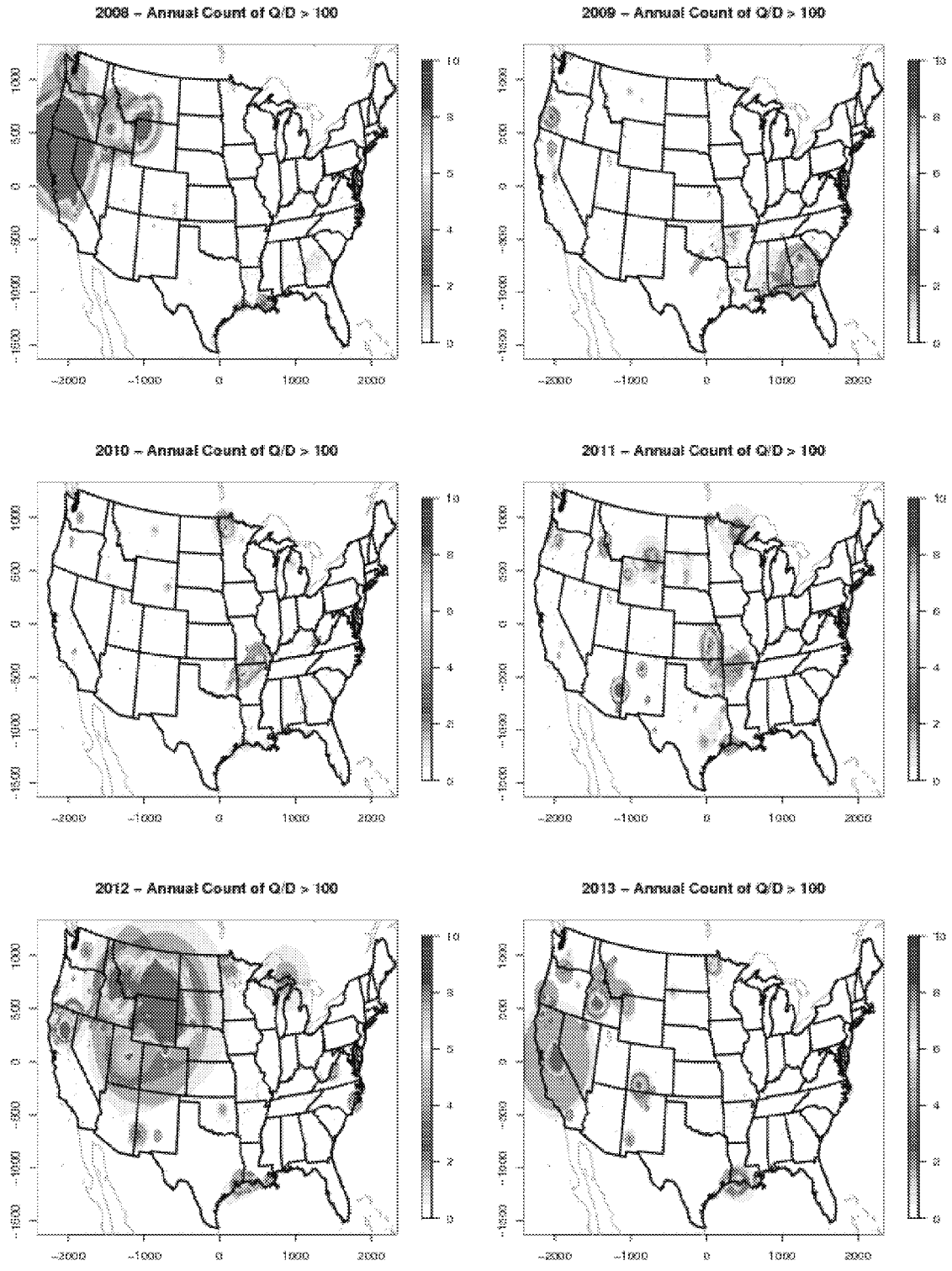
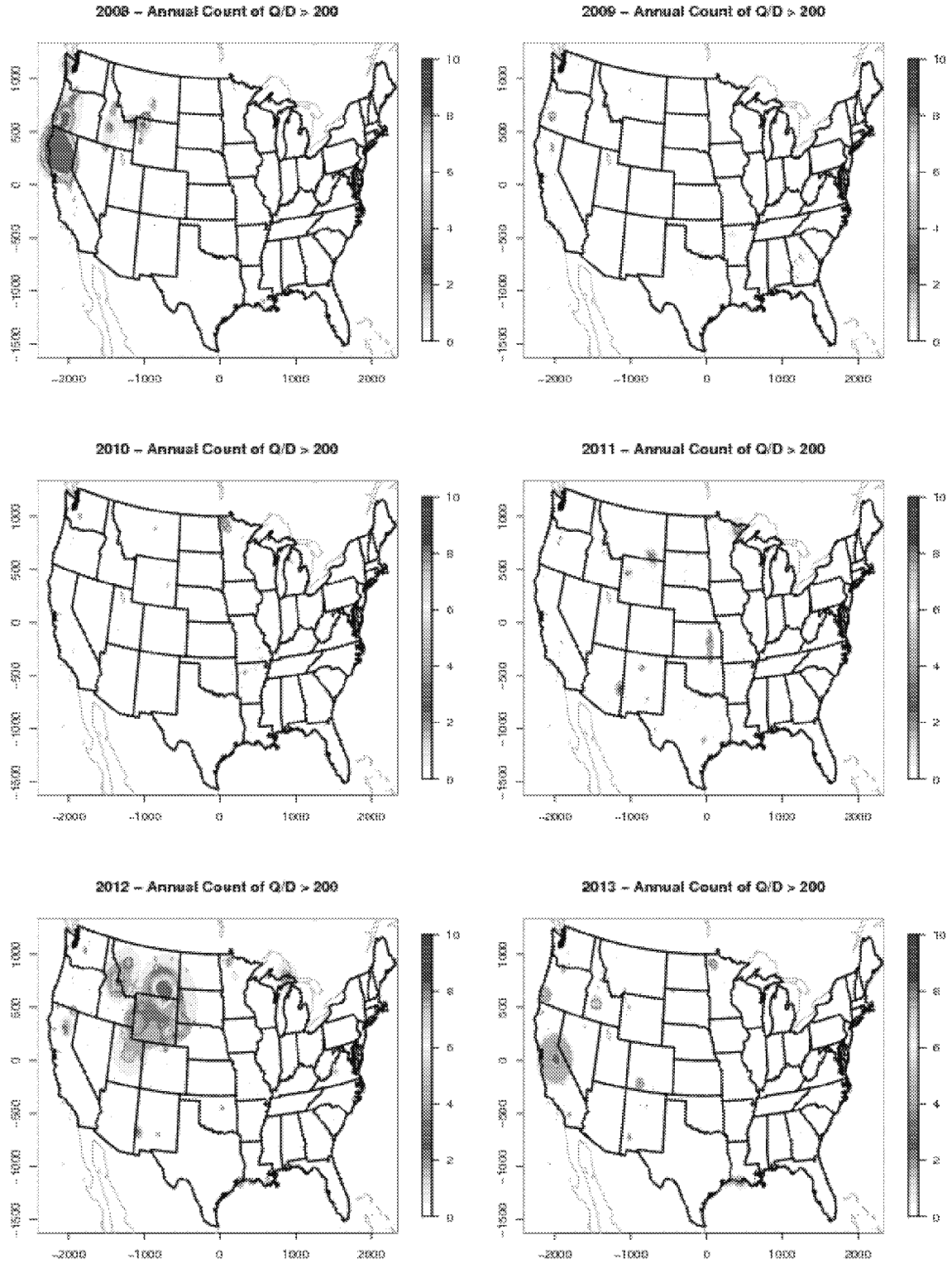


Figure A2-8. Count of days with NOx+rVOC Q/D > 200 for 2008 through 2013. Note scale has been capped at 10 to more easily distinguish the values below 10. Red may actually indicate 10 or greater than 10.



Appendix A3. Interpreting HYSPLIT Results

A HYSPLIT backward trajectory, the most common trajectory used in assessments associated with determining source areas, is usually depicted on a standard map as a single line extending in two dimensional (x,y) space from a starting point, regressing backward in time as the line extends from the starting point. An individual trajectory can have only one starting height; HYSPLIT can plot trajectories of different starting heights at the same latitude/longitude starting point on the same map, automatically using different colors for the different starting heights. HYSPLIT will also include a vertical plot of the trajectories in time, with colors corresponding to the same trajectory in the (x,y) plot. Diurnal mixing height data on flagged days should be considered in setting up the starting point matrix. Caution is needed, because this display can be easily misinterpreted as having finer accuracy than the underlying model and data.

It is important to observe the overall size of the plot, its width and length in kilometers, while considering the size of an individual grid cell in the input meteorological data set. These input grid cells are usually 40 km in width and length, so the total area of a trajectory plot may sometimes represent only a few meteorological grid cells. It is also important to understand the trajectory line itself. The line thickness is predetermined as a user option, so it does not imply coverage other than to represent the centerline of an air parcel's motion calculated to arrive at the starting location at the starting time. The range of the width and the height of plume can vary significantly and are not normally part of the information output but clearly can lead to uncertainty in source strength at the centerline. Uncertainties are clearly present in these results, and these uncertainties can be thought to be a range on either side of the center line in which the air parcel may be found. Further back in time along the trajectory path, that range may be assumed to increase. In other words, one should avoid concluding a region is not along a trajectory's path if that trajectory missed the region by a relatively small distance.

Operating HYSPLIT

Detailed information for downloading, installing, and operating HYSPLIT can be found at these websites:
http://ready.arl.noaa.gov/HYSPLIT.php
http://www.arl.noaa.gov/documents/reports/hysplit_user_guide.pdf
http://www.arl.noaa.gov/documents/reports/arl-224.pdf

HYSPLIT's many setup options allow great flexibility and versatility. However, careful selection and recording of these options is recommended to provide reviewers the ability to reproduce the model results. The following paragraphs describe the options that should be recorded, at a minimum, to reproduce a HYSPLIT model run.

Backward Versus Forward Trajectories. Forward and backward HYSPLIT trajectories use the same scientific treatment and processing. These trajectories only differ in the location of the discrete point of origin (forward) or destination (backward). For analyses to assess the potential impact of a source area such as a wildfire on a discrete point of destination such as an air quality monitor, a backward trajectory is more easily interpretable.

Model Version. If the HYSPLIT trajectory is produced via the NOAA Air Resources Laboratory (ARL) website (*http://ready.arl.noaa.gov/HYSPLIT_traj.php*), note the *"Modified:" date* in the lower-left corner of the webpage, as well as the date the trajectory was produced. If the trajectory is produced using a stand-alone version of HYSPLIT, note *the release date*, which will be displayed after exiting the main GUI screen.

Basic Trajectory Information. Note the *starting time* (YY MM DD HR), the *duration of the trajectory* in hours, and whether the trajectory is *backward or forward.* Note the *latitude and longitude*, as well as the *starting height*, for each *starting location*. Starting height is given by default in meters above ground level (AGL) unless another option is selected. Starting heights are typically no less than 100 meters AGL to avoid direct interference of terrain, and are typically no greater than 1500 meters AGL to confine the air parcel within the mixed layer. Some trajectories can escape the mixed layer, and this result would be considered in the interpretation.
Starting height and starting location will identify the three-dimensional location of the trajectory's latest endpoint in time if a backward trajectory is selected (*i.e.*, the start of a trajectory going backward in time).

Input Meteorological Data Set. Note the *input meteorological data set* used in the HYSPLIT model run. The *original file name* provides sufficient information to identify the data set. Meteorological data fields to run the model are already available for access through the HYSPLIT menu system, or by direct FTP from ARL. The ARL web server contains several meteorological model data sets already converted into a HYSPLIT compatible format in the public directories. Direct access via FTP to these data files is built into HYSPLIT's graphical user interface. The data files are automatically updated on the server with each new forecast cycle. Only an email address is required for the password to access the server. The ARL analysis data archive consists of output from the Global Data Analysis System (GDAS) and the NAM Data Analysis System (NDAS - previously called EDAS) covering much of North America. Both data archives are available from 1997 in semi-monthly files (SM). The EDAS was saved at 80 km resolution every 3-hours through 2003, and then at 40 km resolution starting in 2004. Detailed information on all meteorological data available for use in HYSPLIT can be found in the HYSPLIT4 Users Guide (*http://www.arl.noaa.gov/documents/reports/hysplit_user_guide.pdf*).

Vertical Motion Options. HYSPLIT can employ one of 5 different *methods for computing vertical motion*. A sixth method is to accept the vertical motion values contained within the input meteorological data set, effectively using the vertical motion method used by the meteorological model that created the data set. Note which method was selected as well as the value chosen for *the top of the model*, in meters AGL.

Trajectory Display Options. The HYSPLIT trajectory model generates a text output file of end-point positions. The end-point position file is processed by another HYSPLIT module to produce a Postscript display file or output files in other display formats. Some parameters, such as map projection and size, can be automatically computed based on the location and length of the trajectory, or they can be manually set by the user. While these display options do not directly affect the trajectory information itself, noting these options will eliminate possible misinterpretation of identical trajectories because of differing display options. An important

display option is the choice of *vertical coordinate,* usually set to meters AGL for these assessments.

Appendix A4. References for Entire Guidance Document (not only Section 3)

(References for Appendix A2 are separately identified within Appendix A2.)

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